



Temporal changes in mortality attributed to heat extremes for 57 cities in Northeast Asia

Whanhee Lee^a, Hayon Michelle Choi^a, Dahye Kim^a, Yasushi Honda^b, Yue-Liang Leon Guo^c, Ho Kim^{a,*}

^a Graduate School of Public Health, Seoul National University, Seoul, Republic of Korea

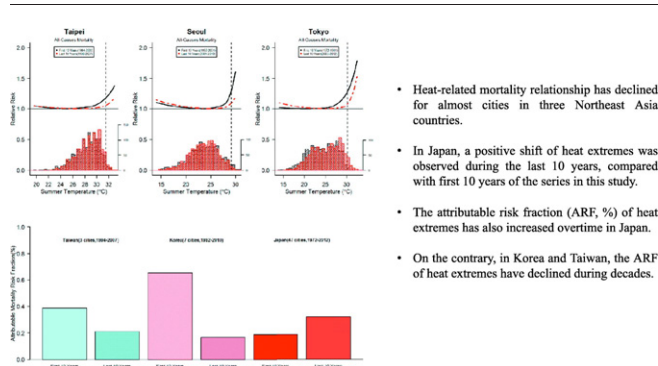
^b Faculty of Health and Sports Sciences, University of Tsukuba, Tsukuba, Japan

^c Department of Environmental and Occupational Medicine, National Taiwan University, Taipei, Taiwan

HIGHLIGHTS

- Heat-related mortality has declined for all three countries.
- In Japan, a positive shift of heat extremes was observed during study period.
- The attributable risk fraction (ARF) of heat extremes increased overtime in Japan.
- The ARF heat extremes temporally declined in Korea and Taiwan.
- We suggest that the ARF of heat extremes will not reduce in climate change.

GRAPHICAL ABSTRACT



- Heat-related mortality relationship has declined for almost cities in three Northeast Asia countries.
- In Japan, a positive shift of heat extremes was observed during the last 10 years, compared with first 10 years of the series in this study.
- The attributable risk fraction (ARF, %) of heat extremes has also increased overtime in Japan.
- On the contrary, in Korea and Taiwan, the ARF of heat extremes have declined during decades.

ARTICLE INFO

Article history:

Received 14 June 2017

Received in revised form 25 October 2017

Accepted 25 October 2017

Available online 3 November 2017

Editor: SCOTT SHERIDAN

Keywords:

Mortality burden

Extreme heat

Climate change

Attributable mortality risk fraction

ABSTRACT

Recent studies have reported that heat-related mortality decreased by adaptation during decades. However, since the frequency of extreme heat events is increasing, it is difficult to conclude with certainty that the heat mortality burden is decreasing. To examine temporal changes in mortality attributed to heat extremes in Northeast Asia, we collected temperature and mortality data covering the years 1972–2012 from 57 cities of 3 countries (Taiwan, Korea, and Japan) in Northeast Asia. Poisson regression curves were fitted to the data from each city. The temporal changes in heat-mortality association were estimated with a time-varying distributed lag non-linear model. Heat extremes were defined as temperatures greater than the 97.5th percentiles of city-specific average temperatures. Attributable deaths were calculated considering temporal variations in exposure and relative risk. The estimates were then pooled through meta-analysis. The results show that the mortality risk on extreme heat days declined during the study period in all countries. However, as summer temperatures in Japan have shown more heat extremes over time, the mortality risk attributed to heat increased during 2003–2012 (0.32%) compared with 1972–1981 (0.19%). Thus, to assess the total health burden due to heat extremes related to climate change, public health strategies should focus on the temporal variation in heat-mortality association as well as changes in the distribution of heat extremes overtime.

© 2017 Elsevier B.V. All rights reserved.

Abbreviations: RR, Relative risk; ARF, Attributable risk fraction; CVD, Cardiovascular; DLNM, Distributed-lag non-linear model; BLUP, Best linear unbiased prediction; MMP, Minimum mortality percentiles.

* Corresponding author at: Department of Public Health Science, Graduate School of Public Health, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 151-742, Republic of Korea.

E-mail address: hokim@snu.ac.kr (H. Kim).

<https://doi.org/10.1016/j.scitotenv.2017.10.258>

0048-9697/© 2017 Elsevier B.V. All rights reserved.

1. Introduction

Health burden due to heat extremes has been a major public health concern for decades, and numerous studies have provided evidence that heat extremes are related to excess risk of mortality (Basu, 2009; Chung et al., 2015; Gasparrini et al., 2015b; Lee et al., 2017). Climate change has increased the intensity and frequency of extreme weather events, with further increases anticipated. According to the National Aeronautics and Space Administration (NASA), the six-month period from January to June of 2016 was the warmest half-year on NASA's global temperature record, and people living in some parts of the northern hemisphere, including Siberia, the Middle East, and North America, faced heat extremes in June and July of that year (Voiland, 2016). Other studies have reported that the second hottest temperature, after the extremes of the 2003 heat wave (Beniston et al., 2017), was observed in many European nations during the summer of 2015, and many parts of the globe experienced extreme heat waves during the summer of 2012, breaking the global average land surface temperature record for June through August (Åström et al., 2013). Therefore, projecting the future health burden related to heat extremes is crucial in establishing future public health strategies and preparing for climate change.

Despite the increase in extreme heat events over the last decades, recent studies have reported temporal attenuation of heat-related mortality, due to adaptation and vulnerability changes (Barnett, 2007; Davis et al., 2003; Gasparrini et al., 2015a). These studies mainly focused on relative risk (RR) of heat extremes on mortality, which has declined overtime (Bobb et al., 2014; Gasparrini et al., 2015a). However, the RR only denotes changes in risk ratio per units of exposure, without considering the distribution of exposure, which has limited ability to predict future health burden due to heat extremes. Furthermore, the majority of previous studies were conducted in western countries (Europe or the United States) (Barnett, 2007; Bobb et al., 2014; Fouillet et al., 2008; Huynen and Martens, 2015). The results of these studies might have limited applicability to Asian regions, because of Asia's different climate and socio-economic factors, which can affect the heat-mortality association.

Therefore, this study aims to investigate decadal-scale change in the mortality burden attributed to heat extremes for 57 cities in three counties of Northeast Asia. The temporal variation of attributable mortality risk fraction (ARF, %), which considers the changes in the distribution and RR of heat extremes (Gasparrini et al., 2015b; Gasparrini and Leone, 2014), is quantified in this study. We based our analysis on a flexible statistical modeling approach (time-varying distributed-lag non-linear model) to account for the non-linear temperature-mortality relationship (Gasparrini et al., 2010). We examine the temporal changes of extreme heat-related mortality through two specific causes of death: cardiovascular and respiratory.

2. Materials and methods

2.1. Data

This study includes data from 57 cities in 3 countries: Taiwan (3 cities during 1994–2007), Korea (7 cities during 1992–2010), and Japan (47 cities during 1972–2012). The Global Research Laboratory (GRL) provided weather and daily death counts for three causes of mortality: all causes, cardiovascular (CVD), and respiratory. CVD mortality is classified by the International Classification of Disease version 8 (ICD-8) (390–458), version 9 (ICD-9) (390–459), and version 10 (ICD-10) (I00–I99) codes. Respiratory mortality is also defined by ICD-8 (460–519), ICD-9 (460–519) and ICD-10 (J00–J99) codes. Weather variables included daily mean temperature (°C), averaged across all temperature monitors for each city. The data were restricted to the summer, identified as the four warmest months (June to September). Additional details on sources of data are reported in Table 1.

2.2. Statistical analysis

2.2.1. First-stage analysis

We first applied the quasi-Poisson regression separately to the data from each city to derive estimates of the city-specific temperature-mortality association (the RRs of temperatures on mortality).

$$Y_t \sim \text{quasi-Poisson}(\lambda_t) \\ \log(\lambda_t) = \beta_0 + s(\mathbf{x}_t; \boldsymbol{\eta}) + \text{factor}(DOW_t) + ns(DOY, df = 4/\text{year}) \\ + ns(\text{Time}, df = 1/10\text{years})$$

where Y_t is the death count on day t , λ_t is the expected death count on day t , and β_0 is an intercept. $s(\cdot)$ is a flexible function characterized by parameter $\boldsymbol{\eta}$ to depict the nonlinear and lagged effects of temperature. We selected cross-basis for exposure with a quadratic B-spline for the exposure-response, two internal knots placed at the 50th and 90th percentiles of the city-specific summer temperature distribution, a natural cubic B-spline for the lag response with an intercept, and two internal knots placed at equally spaced values on the log scale. Ten-day lag periods were selected to capture delayed effects of extreme heat. Seasonality was controlled by using a natural cubic B-spline of day of the year ($ns(DOY, df = 4/\text{year})$) with equally spaced knots and four degrees of freedom (df). Long-term trends were controlled using a natural cubic B-spline with one degree of freedom per ten years ($ns(\text{Time}, df = 1/10\text{years})$). The day of week on day t (DOW_t) was also adjusted as a categorical variable. Choices of modeling assumptions and lag days are based on a previous multi-country scale study (Gasparrini et al., 2015a). The first-stage analysis was performed with the R packages *dlm* (Gasparrini, 2011). We tested these modeling choices with a sensitivity analysis (Table S7).

2.2.2. Time-varying distributed lag non-linear model (DLNM)

In order to apply a time-varying DLNM, we use a special parameterization by defining main and interaction terms in the model.

$$\log(\lambda_t) = \beta_0 + s(\mathbf{x}_t; \boldsymbol{\eta}) + s(\mathbf{x}_t; \boldsymbol{\eta}) : \text{year}_{\text{centered at a median year of each period}} \\ + \text{factor}(DOW_t) + ns(DOY, df = 4/\text{year}) + ns(\text{Time}, df = 1/10\text{years})$$

The main term is the cross-basis ($s(\mathbf{x}_t; \boldsymbol{\eta})$, described in the first-stage analysis), and the interaction term is calculated by multiplying $s(\mathbf{x}_t; \boldsymbol{\eta})$ and the year variable centered at the median of the first and last 10 years of the country-specific periods ($\text{year}_{\text{centered at a median year of each period}}$; Taiwan: 1994–2003 and 1998–2007, Korea: 1992–2001 and 2001–2010, Japan: 1972–1981 and 2003–2012). $s(\mathbf{x}_t; \boldsymbol{\eta})$ consists of 16 parameters obtained by combining the exposure-response and lag-response functions, with 4 df each. In order to simplify the interpretation and use the standard DLNM package in R software, we used the centered year variable. No main term for year variable is needed, because the year effect is already controlled by the flexible spline used to capture the long-term trend, $ns(\text{Time}, df = 1/10\text{years})$. Then, the sets of 16 coefficients of the cross-basis, estimated for median values of the first and last 10 years of the study periods, were reduced to sets of 4 coefficients of uni-dimensional B-splines to represent the lag-cumulative association between temperature and mortality for each city. The four reduced coefficients of each city were used in the second stage of the analysis. This reducing step preserves the complexity of estimated dependency and decreases the number of parameters to be pooled in the second-stage meta-regression. This procedure of time-varying DLNM is well described in a previous study (Gasparrini et al., 2015a).

2.2.3. Second-stage meta-regression

In the second stage analysis, we employed a meta-regression using the R package *mvmeta* to pool the overall cumulative city-specific estimates of the first stage (Gasparrini et al., 2012). We used the city-specific average temperatures and temperature ranges as meta-predictors in a multivariate meta-regression. From this meta-regression, we derived

Table 1

Descriptive statistics by country: number of cities, study periods (divided into first and last 10 years of study periods), total number of deaths, and summer temperature distribution.

Country	(N) of cities	Periods	Deaths (n)			Summer temperature (°C)				
			All	CVD	Respiratory	Min	25%	50%	75%	Max
Taiwan	3	1994–2007	245,587	49,866	19,309	19.5	27.4	28.6	29.5	33
		1994–2003	168,128	34,950	12,568	19.5	27.4	28.6	29.5	33
		1998–2007	182,151	35,479	14,863	19.5	27.5	28.7	29.7	33
Korea	7	1992–2010 ^a	548,561	131,552	26,835	13	21.5	23.6	25.9	33
		1992–2001	274,977	68,084	12,422	13.6	21.5	23.8	26.1	33
		2001–2010	303,130	70,595	16,005	13	21.6	23.6	25.8	31.3
Japan	47	1972–2012	10,889,905	3,529,170	1,256,705	8.6	21.7	24.5	27.1	33.8
		1972–1981	2,112,800	845,320	141,376	8.6	21.2	23.9	26.5	32
		2003–2012	3,411,514	926,110	501,434	10.4	22.4	25.2	27.7	33.7

^a A city of Korea (Ulsan) has different study periods (1997–2010).

the best linear unbiased prediction (BLUP) of the exposure–response associations (the RRs by temperature on mortality) for the medians of the first and last 10 years in each city.

2.2.4. Attributable risk fraction

The minimum mortality temperatures of the two periods (medians of the first and last 10 years), which correspond to minimum mortality percentiles between the 1st and the 99th percentiles of those periods, were derived from the BLUP of time-varying overall cumulative exposure–response relationships (RRs) in each city. We used these minimum mortality temperatures of the two periods as reference values to calculate the time-varying ARF, using a re-centered quadratic B-spline basis for modeling exposure–response. For each city, the overall cumulative RRs, corresponding to temperature of day of series (first and last 10 years of each study periods), were used to calculate the time-varying ARF using a previously reported method (Gasparrini et al., 2015b; Gasparrini and Leone, 2014). For the country-specific ARF, the city-specific attributable numbers of deaths (the product of ARF on day t and death count on day t) were summed by each country. In addition, we calculated the ARF to extreme heat by summing the subsets corresponding to days with temperatures higher than the 97.5th city-specific percentile over the entire study period, consistent with previous extreme heat studies (Gasparrini et al., 2015b; Peng et al., 2011). In order to assess the temporal risk changes at the same temperature, and to consider the variation in the frequency of days that experienced higher temperatures during the study periods, we defined the extreme heat days using the 97.5th percentile over the whole study period, rather than the varying percentile of each period (the first and last 10 years of each study period). We applied the definition method, which was used in previous studies covering similar topics (Chung et al., 2017; Gasparrini et al., 2015a; Hajat et al., 2014; Vardoulakis et al., 2014). We also defined cutoff ranges at the 5th and 1st percentiles (see Table S7), and calculated the empirical confidence intervals (eCI) using Monte Carlo simulations, assuming a multivariate normal distribution of the reduced BLUP.

2.2.5. Statistical test for changes in the overall cumulative exposure–response association

The temporal change in the overall cumulative exposure–response relationship (interaction between a variable and the cross-basis for temperature as the main terms) was assessed through a statistical test. We derived city-specific interaction parameters consisting of 16 coefficients from the “time-varying DLNM” procedures, and reduced them to sets of 4 coefficients using a similar procedure for the main temperature terms. In the second-stage analysis, we also estimated the BLUP of the interaction coefficients and used it for the statistical test. We conducted a multivariate Wald test on the interaction coefficients predicted for each city, accounting for the associated covariance matrix and assuming a multivariate normal distribution. The null hypothesis of the test was that none of the coefficients are different from 0; it means

that there is no change in the overall cumulative exposure–response relationship throughout the study period.

3. Results

Descriptive results are shown in Table 1. The data set includes 11,684,053 deaths from all causes, of which 3,710,588 are attributable to CVD and 1,302,849 are respiratory deaths that occurred during summer within the study periods in the 57 cities. The table also displays the summer temperature for all cities during the first and last 10 years of the study periods. Taiwan and Korea show similar summer temperature distributions between the first and last 10 years (median temperatures: 28.6 °C (first 10 years)–28.7 °C (last 10 years) in Taiwan, and 23.8 °C (first 10 years)–23.6 °C (last 10 years) in Korea). Temperature increased over time in Japan (23.9 °C (first 10 years)–25.2 °C (last 10 years)). The mean temperature over the entire study period for all 57 cities is shown in Fig. 1. Corresponding city-specific descriptive results are reported in Table S2.

The temporal changes in heat-related mortality associations (RRs) and temperature distributions of each representative city of the three countries are summarized in Fig. 2. In Tokyo (Japan) and Taipei (Taiwan), the summer temperature distribution shows a positive shift, with warmer days and more heat extremes in the last 10 years compared with the first 10 years of the series. Distinct differences between the temperature distributions of the first and the last 10 years were not observed in Seoul (Korea). Fig. 2 compares the overall cumulative exposure–response curves predicted from time-varying DLNM for the median of the first 10 years of the study periods (First, solid line) and the median of the last 10 years (Last, dashed line) for the three cities selected to represent each country for all-cause mortality (All) and the two cause-specific deaths. Note that the y-axis is scaled to city-specific ranges. The dashed vertical lines represent the 97.5th percentiles of temperature (as heat extremes) for each city. The analysis suggests a decrease in all causes of mortality associated with heat extremes for all three cities.

The city-specific RRs at the 97.5th percentile, (referenced at minimum mortality percentiles (MMP)) during the first and last ten years and tests for the year–interaction are shown for each city in Tables S3–S5. Strong evidence ($p < 0.05$; H_0 : There is no change in the overall cumulative exposure–response relationship throughout the study period) of time dependence in the temperature–all-cause mortality (Table S3) curve is evident for Tokyo ($p = 0.001$), but little evidence of this is seen for Seoul ($p = 0.198$) and Taipei ($p = 0.335$). Respiratory deaths (Table S5) show the strongest evidence of temporal changes in the curves for all cities (Taipei: $p = 0.004$, Seoul: $p < 0.001$, and Tokyo: $p < 0.001$). CVD mortality (Table S4) also shows significant attenuation in RR over time (Taipei: $p = 0.002$, Seoul: $p = 0.012$, and Tokyo: $p = 0.006$). In addition, the MMP of the last 10 years for all types of mortality increased compared with the MMP of first 10 years of the study periods, except for all-cause and respiratory deaths in Korea, and CVD deaths in Taiwan (Table 2). The corresponding graphs for all 57 cities are

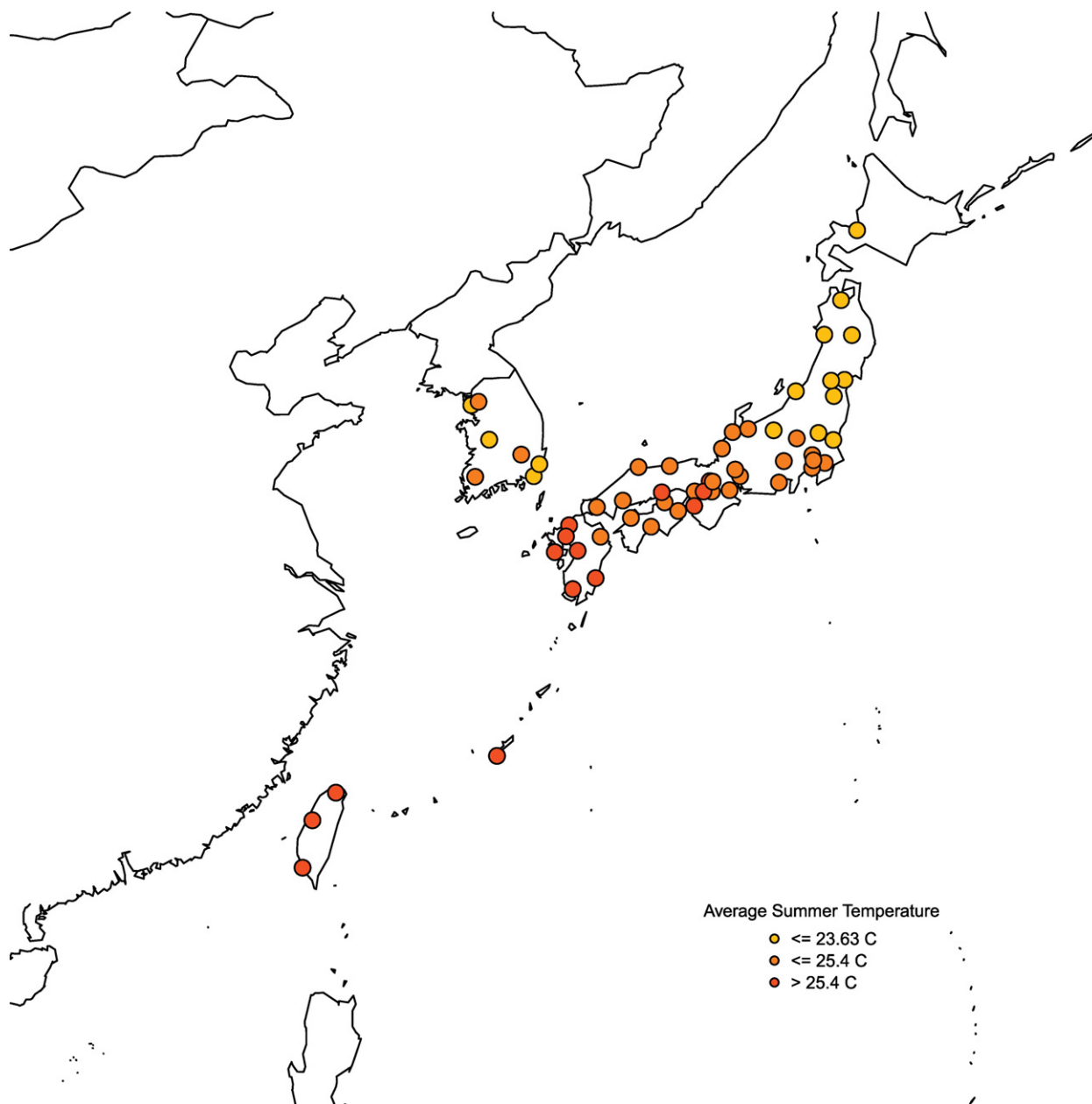


Fig. 1. Geographic locations of the 57 cities of three countries included in the analysis, and corresponding annual mean temperatures (°C) during summer.

provided in the supplementary materials (Fig. S2). The heat–mortality associations estimated from the model without interaction, which can be interpreted as the average throughout the study periods, are also shown in Fig. S1. Fig. S3 shows the effect modification of time on overall cumulative heat-related mortality associations estimated from the interaction model in the 57 cities. Fig. S4 is similar to Fig. 2; however, it shows curves with different 97.5th percentile temperatures for the first and last 10 years of the study periods. This decreasing RR of extreme heat was observed both with time-constant percentiles (Fig. 2) and time-dependent percentiles (Fig. S4).

The main findings (Table 2 and Fig. 3) of the analysis are the temporal changes in ARF caused by heat extremes in each country. In Japan, a positive shift of heat extremes was observed during the last 10 years, compared with first 10 years of the series, and the ARF due to extreme heat also increased overtime for all types of mortality (all-cause deaths increased by 0.13%, CVD by 0.34%, and respiratory by 0.02%) while the corresponding RR of heat extremes decreased with time (see Fig. 2).

Comparison of 95% confidence intervals between the ARF of the first and last 10 years shows that the temporal increases of ARF for all-cause and CVD deaths are significant in Japan. However, the ARF of heat extremes for all mortality types declined over time in Korea and Taiwan. Specifically, the ARF of heat extremes dropped between the first and last 10 years (all-cause deaths decreased by 0.48%, CVD deaths by 0.55%, and respiratory deaths by 1.32%) in Korea. In Taiwan, the decreases in ARF over these intervals is also apparent (all-cause deaths decreased by 0.18%, CVD deaths by 0.22%, and respiratory deaths by 0.97%). The corresponding ARF values for all 57 cities are provided in the supplementary materials (Table S6).

Sensitivity analyses were performed to test the consistency of the results with various definitions of the first and last periods (5 and 7 years), and modeling assumptions. To avoid interpretation complexity, only all-cause mortality was used. The results of these sensitivity analyses (Table S7) indicate that our results are not dependent on the modeling assumptions (*df* of seasonal control, long-term trend, the lag-response

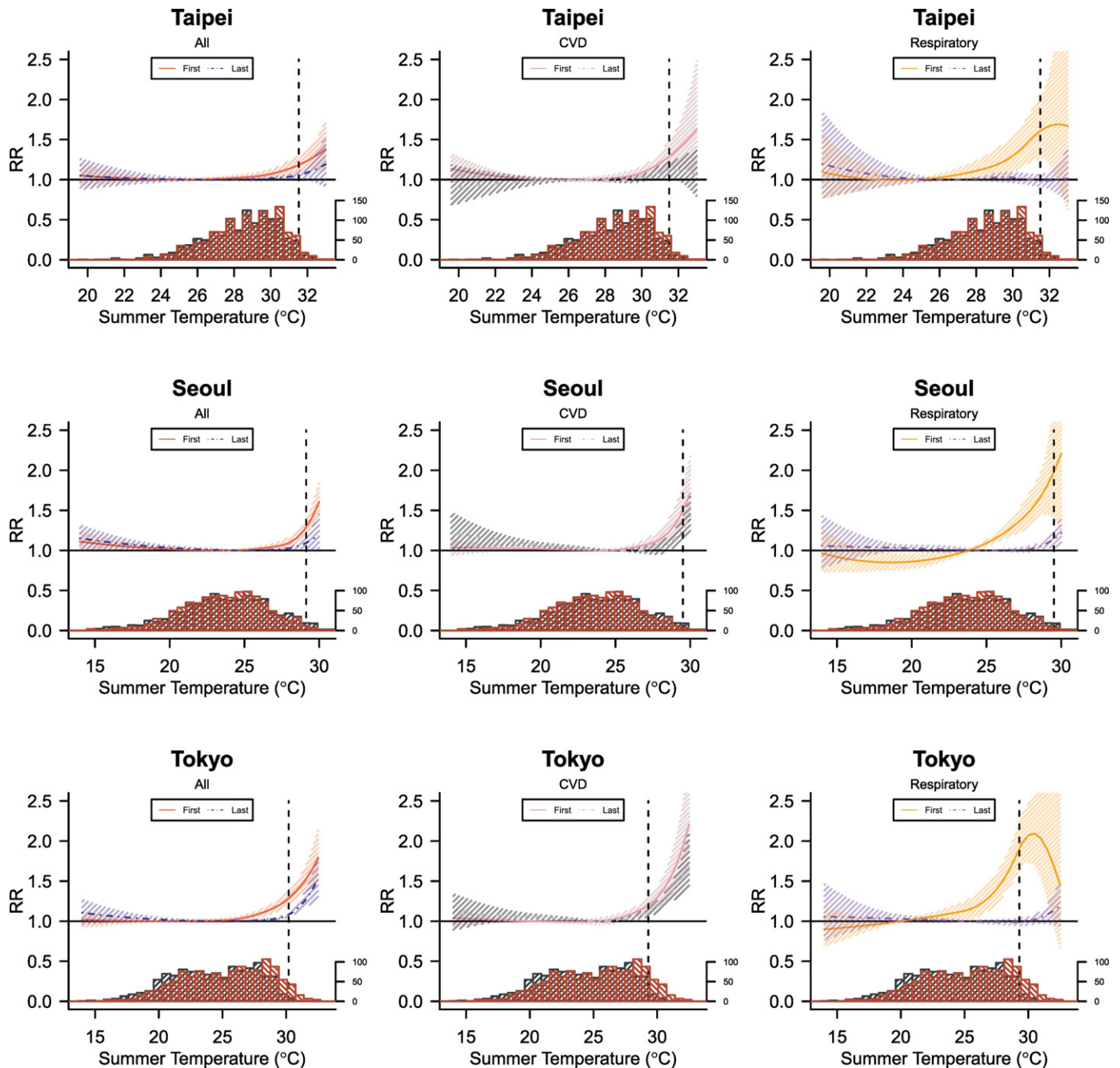


Fig. 2. Overall cumulative exposure–response curves for overall and two heat-related mortalities (Overall, CVD, Respiratory; predicted for a median of the first 10 years of study periods (First; Red, Pink, Orange) and a median of the last 10 years of the series (Last; Blue, Grey, Purple)) in each representative city of three countries, with temporal changes in temperature distributions during summer. The vertical lines represent the 97.5th percentile of temperature (heat extremes) for each city.

relationship, and the exposure–response relationship; lag periods for the heat extreme; years of the first and last periods; and cutoffs for extreme heat days).

4. Discussion

This study finds that ARF due to heat extremes has changed over the last decades in 57 cities of 3 countries in Northeast Asia. For Japan, the results of which show the highest statistical power, the ARF of all-cause deaths during heat extremes increased significantly in the last 10 years of the series (ARF: 0.32% with 95% CI: 0.27–0.37%) compared with the first 10 years (ARF: 0.19% with 95% CI: 0.18–0.2%) even though extreme heat-related mortality (RR) declined during the study period.

The two cause-specific (CVD and respiratory) deaths displayed the same temporal trend as all-cause mortality. In Taiwan and Korea, however, the RR and ARF of extreme heat decreased for all three types of mortality during the study periods. The study shows that, as more heat-extreme days have occurred over recent decades, the total mortality burden attributed to extreme heat increased in Japan. Furthermore, the temporal changes in the risk of death from extreme temperatures and the distribution of extreme heat temperatures should be considered as predictive of the future impacts of heat extremes on health resulting from climate change.

Extreme hot temperature has been a well-known weather-related risk factor for death globally, thus previous studies have focused the effect of extreme heat on mortality among the Asian population. Zeng et

Table 2
Results by country: minimum mortality percentile (MMP), period used to prediction (at median of first and last 10 years of study periods), Attributable risk fraction (ARF) due to heat extremes (95% CI) for three cause-specific deaths (all-cause deaths (All), cardiovascular disease (CVD), and respiratory death).

Cause of death	Country	At first 10 years		At last 10 years	
		MMP (%)	ARF (%)	MMP (%)	ARF (%)
All cause	Taiwan	4	0.39 (0.22, 0.53)	16	0.21 (0.03, 0.38)
	Korea	44	0.65 (0.51, 0.77)	44	0.17 (0.04, 0.28)
	Japan	20	0.19 (0.18, 0.2)	58	0.32 (0.27, 0.37)
CVD	Taiwan	11	0.49 (0.24, 0.69)	1	0.27 (0.01, 0.49)
	Korea	54	0.78 (0.5, 1.01)	62	0.23 (0.15, 0.3)
	Japan	46	0.24 (0.22, 0.25)	63	0.58 (0.51, 0.63)
Respiratory	Taiwan	2	0.99 (0.47, 1.3)	4	0.02 (−0.2, 0.2)
	Korea	7	1.61 (1.05, 1.96)	1	0.29 (0.14, 0.41)
	Japan	2	0.38 (0.32, 0.41)	25	0.4 (0.3, 0.48)

al. reported that the extreme heat was related with an increasing mortality risk (8.2% with 95% CI: 3.4–13.2%) in four communities of Guangdong province in China, and suggested that the risks were higher for rural areas, elderly population, and cardiovascular-respiratory patients (Zeng et al., 2014). Ma et al. also showed that the heat wave effects on mortality were higher for elderly and cardiovascular-respiratory deaths in 66 Chinese communities, however the effects were higher for the urban areas contrary to the results of Zeng et al. (2014). (Ma et al., 2015b). Our study also reported the higher heat-extreme risks for cardiovascular-respiratory deaths, compared to those for all-causes mortality. However, our study did not find any significant risk increases (or decreases) in urban or densely populated areas, and could not consider the age-stratified effect modification due to data limitation. In addition, Ma et al. found that the heat-related mortality association varies geographically and the association was more pronounced in colder region (northern communities) (Ma et al., 2015a). This phenomenon is also observed in our study, and acclimatization to local weather conditions have been adduced as a major hypothesis of these regional variations in the heat-related mortality relationship (Anderson and Bell, 2009; Curriero et al., 2002).

Our results (increasing MMP and decreasing extreme heat-related mortality) provide evidence that these three Northeast Asian countries have adapted well to extreme heat, and these findings are generally consistent with previous investigations: Ha et al. were estimated a decrease from 8.69% in the 1990s to 5.27% in the 2000s with regard to the risk for cardiovascular mortality associated with a 1 °C increase above 27.2 °C in Seoul during summer (Ha and Kim, 2013). Gasparrini et al. (2015a) reported a significant decrease ($p < 0.001$) in Japan, with RR at the 99th percentile changing from 1.161 in 1993 to 1.061

in 2006 (Gasparrini et al., 2015a). Although there are several other plausible hypotheses, including economic growth, developments in weather forecasting, public health service, and popularization of air conditioning (Anderson and Bell, 2009; Bobb et al., 2014; Gasparrini et al., 2015a), the exact drivers of this reduced risk could not be identified in our study. More comprehensive analysis must be conducted to identify the causes of the observed temporal variation. In all three countries, temporal trends in the heat-related mortality (RR) are similar between all-cause deaths and CVD. While the magnitude of the decrease in the heat-related respiratory mortality was greater, despite the increased rate of respiratory death (compared to all-cause death) in all three countries, comparing the first 10 years to the last 10 years of the study periods, with an increase of 0.7% in Taiwan, 0.8% in Korea and 8.0% in Japan, calculated from Table 1. These temporal increases in respiratory death rate might be a result of the aging population in all three countries. A previous study, focused on asthma, proposed that protective outcomes in aged persons might result, in part, from adaptive behaviors of patients with respiratory disease, such as staying inside when the outdoor climate is unfavorable (Kim et al., 2014). However, the reasons for lower respiratory mortality risk due to heat extremes are still uncertain and should be researched further.

In all three countries, temporal trends in heat-related mortality (RR) are similar for all-cause and CVD deaths. Comparing the first 10 years to the last 10 years of the study periods shows that the magnitude of the decrease in the heat-related respiratory mortality was greater despite the increased rate of respiratory deaths (compared to all-cause deaths) in all three countries. These temporal increases in respiratory death rate might be a result of the aging population in all three countries. A previous study, focused on asthma, proposed that protective outcomes in

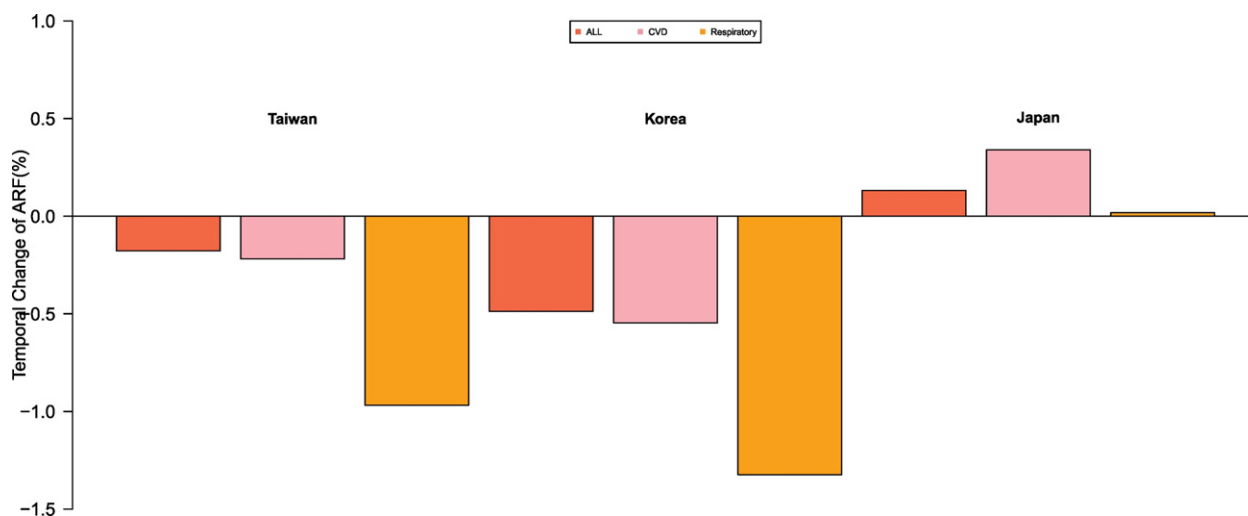


Fig. 3. Incremental rate of mortality risk fractions (ARF, %) attributed to heat extremes for three types of mortality (all-cause (All), cardiovascular disease (CVD), and respiratory) in the last 10 years of study periods compared with the first 10 years.

aged persons might result, in part, from adaptive behaviors of patients with respiratory disease, such as staying inside when the outdoor climate is unfavorable (Kim et al., 2014). However, the reasons for lower respiratory mortality risk due to heat extremes are still uncertain and should be researched further.

We also found that patterns of the temporal changes in ARF differ from those in RR. In Japan, the ARFs of heat extremes have increased during the last decade, while the corresponding RRs decreased. The ARFs for Taiwan and Japan decreased in our results; although future heat extremes are likely to become more common, the ARFs are likely to increase. The variation in the time trends of ARF for heat extremes is caused by changes in the frequency of these events. Most previous studies projecting changes in risk due to extreme temperature events only focused on risk per unit of exposure (RR) (Bobb et al., 2014; Carson et al., 2006; Gasparrini et al., 2015a). Our results show that this can lead to misunderstanding the impacts of extreme heat on mortality. In particular, as climate warming progresses, considering the changing distribution of extreme weather events could be a key element in heat-mortality burden projections; we therefore suggest that the ARF, which considers exposure risk and days of extreme heat, is a better index to assess total health impacts from heat (Hajat and Gasparrini, 2016).

This study has some limitations. First, we did not consider age-specific heat-related mortality relationships due to data limitations. Varied adaptations to heat among different age groups have been reported (Bobb et al., 2014), and age-specific analysis should be a topic of further study. Second, our study did not consider any competing effects of air pollution; it has been argued, however, that air pollution should not confound temperature-mortality relationships (Buckley et al., 2014). Third, local ecological variables in this study (across multiple monitors in each city) were averaged to determine city-specific values, creating the assumption of spatial homogeneity for each city. Although urbanization and other area-specific abnormal phenomena such as heat-island effects may influence the spatial heterogeneity of heat extreme-related mortality association, we were not able to consider such phenomena while estimating the health burden attributed to heat extremes in this study. Fourth, the current findings cannot necessarily be interpreted as being representative of other cities and countries with different socioeconomic characteristics and climate conditions.

We examined the temporal changes in mortality burden due to heat extremes for 57 cities of 3 countries in Northeast Asia. The temporal decrease in RR is a suitable index for identifying adaptation to heat. However, this index cannot be used to estimate future health burdens attributed to heat, because it cannot reflect changing exposure distribution over time. To address this limitation, we suggest the use of ARF to estimate future mortality burdens due to heat extremes. As the frequency of extreme heat events has increased over recent decades in Japan, the ARF related to these heat extremes increased over the period 2003–2012 compared with the years 1972–1981, while the RR of heat extremes has declined. We expect that our results can be used to predict the increased health burden due to more frequent heat extremes, and to prepare corresponding public health policies. Furthermore, our results suggest that national and international efforts toward reducing greenhouse gas emissions, which are related to the increased frequency of high-temperature events, are crucial to reduce the future health burden attributed to heat extremes.

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2017.10.258>.

Acknowledgements

This subject is supported by Korea Ministry of Environment as “Climate Change Correspondence Program (project number: 2014001310007)” and the National Research Foundation of Korea Grant funded by the Korean Government (No. 21B20151213037).

References

- Anderson, B.G., Bell, M.L., 2009. Weather-related mortality: how heat, cold, and heat waves affect mortality in the United States. *Epidemiology* 20, 205.
- Åström, D.O., Forsberg, B., Ebi, K.L., Rocklöv, J., 2013. Attributing mortality from extreme temperatures to climate change in Stockholm, Sweden. *Nat. Clim. Chang.* 3, 1050.
- Barnett, A.G., 2007. Temperature and cardiovascular deaths in the US elderly: changes over time. *Epidemiology* 18, 369–372.
- Basu, R., 2009. High ambient temperature and mortality: a review of epidemiologic studies from 2001 to 2008. *Environ. Health* 8, 40.
- Beniston, M., Stoffel, M., Guillet, S., 2017. Comparing observed and hypothetical climates as a means of communicating to the public and policymakers: the case of European heatwaves. *Environ. Sci. Pol.* 67, 27–34.
- Bobb, J.F., Peng, R.D., Bell, M.L., Dominici, F., 2014. Heat-related mortality and adaptation to heat in the United States. *Environ. Health Perspect.* 122, 811 (Online).
- Buckley, J.P., Samet, J.M., Richardson, D.B., 2014. Commentary: does air pollution confound studies of temperature? *Epidemiology* 25, 242–245.
- Carson, C., Hajat, S., Armstrong, B., Wilkinson, P., 2006. Declining vulnerability to temperature-related mortality in London over the 20th century. *Am. J. Epidemiol.* 164, 77–84.
- Chung, Y., Lim, Y.H., Honda, Y., Guo, Y.L., Hashizume, M., Bell, M.L., et al., 2015. Mortality related to extreme temperature for 15 cities in northeast Asia. *Epidemiology* 26, 255–262.
- Chung, Y., Noh, H., Honda, Y., Hashizume, M., Bell, M.L., Guo, Y.-L.L., et al., 2017. Temporal changes in mortality related to extreme temperatures for 15 cities in Northeast Asia: adaptation to heat and maladaptation to cold. *Am. J. Epidemiol.* 185, 907–913.
- Curriero, F.C., Heiner, K.S., Samet, J.M., Zeger, S.L., Strug, L., Patz, J.A., 2002. Temperature and mortality in 11 cities of the eastern United States. *Am. J. Epidemiol.* 155, 80–87.
- Davis, R.E., Knappenberger, P.C., Michaels, P.J., Novicoff, W.M., 2003. Changing heat-related mortality in the United States. *Environ. Health Perspect.* 111, 1712.
- Fouillet, A., Rey, G., Wagner, V., Laaidi, K., Empereur-Bissonnet, P., Le Tertre, A., et al., 2008. Has the impact of heat waves on mortality changed in France since the European heat wave of summer 2003? A study of the 2006 heat wave. *Int. J. Epidemiol.* 37, 309–317.
- Gasparrini, A., 2011. Distributed lag linear and non-linear models in R: the package dlnm. *J. Stat. Softw.* 43, 1.
- Gasparrini, A., Leone, M., 2014. Attributable risk from distributed lag models. *BMC Med. Res. Methodol.* 14, 1.
- Gasparrini, A., Armstrong, B., Kenward, M.G., 2010. Distributed lag non-linear models. *Stat. Med.* 29, 2224–2234.
- Gasparrini, A., Armstrong, B., Kenward, M., 2012. Multivariate meta-analysis for non-linear and other multi-parameter associations. *Stat. Med.* 31, 3821–3839.
- Gasparrini, A., Guo, Y., Hashizume, M., Kinney, P.L., Petkova, E.P., Lavigne, E., et al., 2015a. Temporal Variation in Heat-Mortality Associations: A Multicountry Study.
- Gasparrini, A., Guo, Y., Hashizume, M., Lavigne, E., Zanobetti, A., Schwartz, J., et al., 2015b. Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *Lancet* 386, 369–375.
- Ha, J., Kim, H., 2013. Changes in the association between summer temperature and mortality in Seoul, South Korea. *Int. J. Biometeorol.* 57, 535–544.
- Hajat, S., Gasparrini, A., 2016. The excess winter deaths measure: why its use is misleading for public health understanding of cold-related health impacts. *Epidemiology* 27, 486.
- Hajat, S., Vardoulakis, S., Heaviside, C., Eggen, B., 2014. Climate change effects on human health: projections of temperature-related mortality for the UK during the 2020s, 2050s and 2080s. *J. Epidemiol. Community Health* 68, 641–648.
- Huynen, M.M., Martens, P., 2015. Climate change effects on heat- and cold-related mortality in the Netherlands: a scenario-based integrated environmental health impact assessment. *Int. J. Environ. Res. Public Health* 12, 13295–13320.
- Kim, J., Lim, Y., Kim, H., 2014. Outdoor temperature changes and emergency department visits for asthma in Seoul, Korea: a time-series study. *Environ. Res.* 135, 15–20.
- Lee, W.-H., Lim, Y.-H., Dang, T.N., Seposo, X., Honda, Y., Guo, Y.-L.L., et al., 2017. An investigation on attributes of ambient temperature and diurnal temperature range on mortality in five East-Asian countries. *Sci Rep* 7, 10207.
- Ma, W., Wang, L., Lin, H., Liu, T., Zhang, Y., Rutherford, S., et al., 2015a. The temperature-mortality relationship in China: an analysis from 66 Chinese communities. *Environ. Res.* 137, 72–77.
- Ma, W., Zeng, W., Zhou, M., Wang, L., Rutherford, S., Lin, H., et al., 2015b. The short-term effect of heat waves on mortality and its modifiers in China: an analysis from 66 communities. *Environ. Int.* 75, 103–109.
- Peng, R.D., Bobb, J.F., Tebaldi, C., McDaniel, L., Bell, M.L., Dominici, F., 2011. Toward a quantitative estimate of future heat wave mortality under global climate change. *Environ. Health Perspect.* 119, 701–706.
- Vardoulakis, S., Dear, K., Hajat, S., Heaviside, C., Eggen, B., AJ, McMichael, 2014. Comparative assessment of the effects of climate change on heat- and cold-related mortality in the United Kingdom and Australia. *Environ. Health Perspect.* 122, 1285.
- Voiland, A., 2016. Extreme Heat for an Extreme Year. NASA Earth Observatory. NASA Goddard Institute of Space Studies (GISS), NASA Earth Observatory.
- Zeng, W., Lao, X., Rutherford, S., Xu, Y., Xu, X., Lin, H., et al., 2014. The effect of heat waves on mortality and effect modifiers in four communities of Guangdong Province, China. *Sci. Total Environ.* 482, 214–221.